

# STATUS OF SPIN PHYSICS

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Fundamental spin physics has made striking progresses in the last years; new ideas, experiments and data interpretations have been proposed and keep emerging. A review of some of the most important issues in the spin structure of nucleons is made and prospects for the future are discussed.

## 1 Introduction

Since the so called proton spin crisis in the parton model<sup>1,2</sup> – a little more than a decade ago – high energy spin physics has experienced an impressive blooming in the amount of proposed and performed experiments, of new theoretical ideas, of interest in issues where spin plays a crucial role. There is by now a general consensus on the fact that spin represents a fundamental, quantum mechanical and relativistic, aspect of QCD field theory, which has to be fully understood before we can claim that a good knowledge of the nucleon and hadron structures has been achieved.

A proof of the richness of spin physics is the difficulty in confining the subject in half an hour talk and the written version in a limited numbers of pages. I'll try to choose the arguments by following the logic line of looking into the proton structure, asking what we know about it. It leads us along the following path:

- how and what do we know about the polarized structure functions  $g_1(x, Q^2)$  and  $g_2(x, Q^2)$ ?
- how and what do we know about quark and gluon helicity distributions,  $\Delta q(x, Q^2)$  and  $\Delta g(x, Q^2)$ ?
- how and what do we know about quark and gluon orbital angular momentum,  $L_q$  and  $L_g$ ?
- $\Delta q(x, Q^2)$ ,  $\Delta g(x, Q^2)$ ,  $L_q$  and  $L_g$  are not the whole story: how and where do we learn about the transversity distribution  $h_1(x, Q^2)$ ?
- Transversity, a chiral-odd function, needs other chiral-odd functions in order to be accessible, and this leads to azimuthal asymmetries in semi-inclusive DIS,  $\ell p^\uparrow \rightarrow \ell \pi X$ , or to a measurement of  $\Lambda$  polarization,  $\ell p^\uparrow \rightarrow \ell \Lambda^\uparrow X$ .

At the end, I would like to make also some comments on the “small”  $Q^2$  transition region, where interesting results have recently been obtained on the Bloom-Gilman duality for  $g_1$  and on the electromagnetic elastic proton form factors. I will not have time to comment on the unexplored regions that the planned  $\nu$ -factory experiments<sup>3</sup> – neutrino initiated DIS with *polarized* targets – might open in the not so near future. Lack of time and space also force me to ignore several other important issues.

## 2 Polarized structure functions

The polarized structure functions  $g_1$  and  $g_2$  appear in the antisymmetric part of the hadronic tensor and are measured by combining polarized DIS cross-sections:

$$\frac{d^2\sigma^{\overrightarrow{\leftarrow}}}{d\Omega dE'} - \frac{d^2\sigma^{\overrightarrow{\rightarrow}}}{d\Omega dE'} = \frac{4\alpha^2 E'}{Q^2 E M \nu} [(E + E' \cos \theta) g_1 - 2Mx g_2] \quad (1)$$

and

$$\frac{d^2\sigma^{\rightarrow\Downarrow}}{d\Omega dE'} - \frac{d^2\sigma^{\rightarrow\Uparrow}}{d\Omega dE'} = \frac{4\alpha^2 E'^2}{Q^2 E M \nu} \sin \theta \left[ g_1 + \frac{2E}{\nu} g_2 \right], \quad (2)$$

which are written in terms of typical DIS variables, following the usual conventions for longitudinal ( $\rightarrow, \Rightarrow, \Leftarrow$ ) and transverse polarizations ( $\Uparrow, \Downarrow$ )<sup>4</sup>.

The polarized structure functions  $g_1$  and  $g_2$  are actually extracted from data on double spin asymmetries,

$$A_{\parallel} \equiv \frac{d\sigma^{\overrightarrow{\leftarrow}} - d\sigma^{\overrightarrow{\rightarrow}}}{d\sigma^{\overrightarrow{\rightarrow}} + d\sigma^{\overrightarrow{\leftarrow}}}, \quad A_{\perp} \equiv \frac{d\sigma^{\rightarrow\Downarrow} - d\sigma^{\rightarrow\Uparrow}}{d\sigma^{\rightarrow\Uparrow} + d\sigma^{\rightarrow\Downarrow}}, \quad (3)$$

and by now a good amount of information is available on  $g_1$  [see Fig. 1] and some first information on  $g_2$ <sup>5</sup> [see Fig. 2]. This information is interpreted in the framework of the QCD parton model.

## 3 Extraction of $\Delta q$ and $\Delta g$

At NLO in the QCD parton model the structure function  $g_1$  is given by

$$g_1(x, Q^2) = \frac{1}{2} \sum_q e_q^2 \left\{ \Delta C_q \otimes [\Delta q + \Delta \bar{q}] + \frac{1}{N_f} \Delta C_g \otimes \Delta g \right\} \quad (4)$$

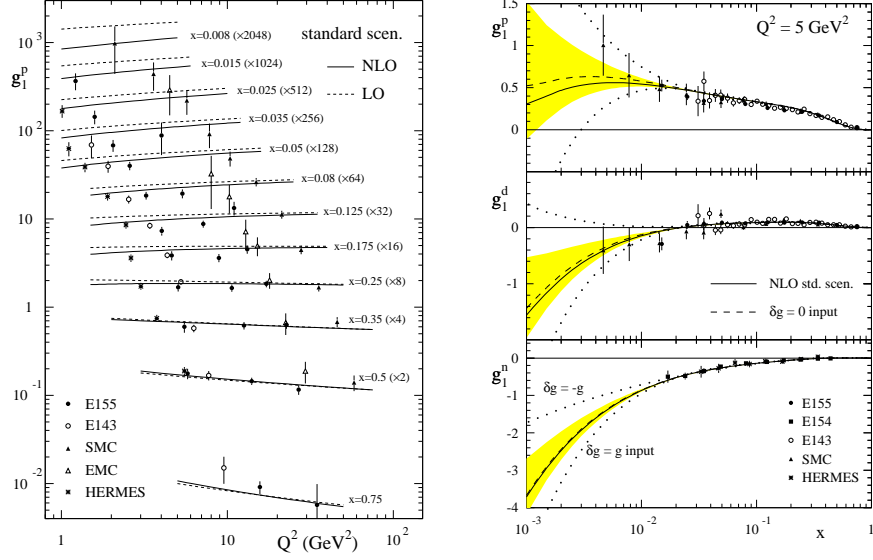


Figure 1: World data on  $g_1$  and best fits from Ref. [8].

where  $\Delta q(x, Q^2)$  and  $\Delta g(x, Q^2)$  are respectively the quark (of flavour  $q$ ) and gluon helicity distributions; we have, as usual, defined the convolution

$$\Delta C \otimes \Delta q \equiv \int_x^1 \frac{dy}{y} \Delta C\left(\frac{x}{y}, \alpha_s\right) \Delta q(y, Q^2) \quad (5)$$

and the coefficients functions  $\Delta C_i$  have a perturbative expansion

$$\Delta C_i(x, \alpha_s) = \Delta C_i^0(x) + \frac{\alpha_s(Q^2)}{2\pi} \Delta C_i^{(1)}(x) + \dots \quad (6)$$

The LO terms are simply

$$\Delta C_q^0 = \delta(1-x) \quad \Delta C_g^0 = 0, \quad (7)$$

and the NLO corrections are scheme dependent; typical choices differ in the amount of gluon contribution to the quark singlet distributions, while quark non-singlet distributions are scheme independent<sup>6</sup>. Finally, the  $Q^2$  evolution of the parton densities obeys the DGLAP evolution equations<sup>7</sup>, and, if known

at an initial scale  $\mu^2$ , the r.h.s. of Eq. (4) can be computed at any perturbative  $Q^2$  value.

By comparing data on  $g_1(x, Q^2)$  with Eq. (4) one obtains information on the quark and gluon helicity distributions; the more data one has and the wider the  $x$  and  $Q^2$  range is, the more stringent the comparison is. The normal procedure is that of using a simple ansatz for the unknown distribution functions at the initial scale  $\mu^2$ , with some assumptions regarding the sea quark densities (for example, whether  $SU(3)_F$  symmetric or not) and some constraints from  $SU(3)_F$  hyperon decay sum rules on the first moments  $\Delta q(1, Q^2) \equiv \int_0^1 \Delta q(x, Q^2) dx$ <sup>6,8</sup>:

$$\Delta q_3 \equiv \Delta u(1) + \Delta \bar{u}(1) - \Delta d(1) - \Delta \bar{d}(1) = 1.2670 \pm 0.0035 \quad (8)$$

$$\Delta q_8 \equiv \Delta u(1) + \Delta \bar{u}(1) + \Delta d(1) + \Delta \bar{d}(1) - 2[\Delta s(1) + \Delta \bar{s}(1)] = 0.58 \pm 0.15.$$

Fig. 1 shows recent fits to  $g_1$  data; details can be found in Ref.<sup>8</sup>. The  $Q^2$  QCD evolution is well reproduced at all available  $x$  values; the lack of small  $x$  data does not allow yet to constrain the gluon distribution, which only enters indirectly, via density evolution. The dotted lines in the right plot of Fig. 1 show variations on  $g_1$  corresponding to the two possible extreme cases for  $\Delta g$  at the initial scale: either  $\Delta g = g$  or  $\Delta g = -g$ . The shaded areas correspond to a variation of  $\Delta g(1, Q^2 = 5 \text{ (GeV/c)}^2)$  between  $-0.81$  and  $1.73$ . In these fits a  $SU(3)_F$  symmetric polarized sea has been assumed,  $\Delta u_s = \Delta \bar{u} = \Delta d_s = \Delta \bar{d} = \Delta s = \Delta \bar{s}$ ; releasing this assumption does not significantly change the quality of the fit.

Inclusive polarized DIS scattering data do not allow yet a complete precise determination of the gluon and the sea helicity distributions.

### 3.1 Direct measurement of $\Delta g(x, Q^2)$

Undoubtely, a direct measurement of  $\Delta g(x, Q^2)$ , in a process different from inclusive DIS, is one of the most urgent and important issues in spin physics; there are many plans and projects for such a measurement, in running or planned experiments (HERMES, RHIC, COMPASS) or proposed ones (HERA- $\vec{N}$ , TESLA- $\vec{N}$ , ELFE, EIC, ...). A very first measure of  $\Delta g(x)/g(x)$  is already available, although with large errors and at one single value of  $x$ , from HERMES<sup>9</sup>.

One should look for  $\Delta g$  in processes involving polarized gluons, and measure spin asymmetries; one can isolate polarized gluon contributions by carefully selecting final states and/or by selecting particular kinematical regions where gluons are supposed to dominate. Processes in which one could isolate  $\gamma^*g$  elementary contributions are:

- $\vec{\ell}\vec{N} \rightarrow \ell + 2 \text{ jets};$
- $\vec{\ell}\vec{N} \rightarrow \ell + h_1 + h_2 + X$ , where  $h_1$  and  $h_2$  are large  $p_T$  hadrons;
- $\vec{\ell}\vec{N} \rightarrow \ell + c + \bar{c} + X.$

Quarks and gluons are supposed to initiate prompt photon production:

- $\vec{p}\vec{N} \rightarrow \gamma X,$

and  $gg$  interactions might dominate in

- $\vec{p}\vec{N} \rightarrow 2 \text{ jets} + X$
- $\vec{p}\vec{N} \rightarrow h_1 + h_2 + X .$

### 3.2 Flavour decomposition

From data on inclusive DIS one only obtains information on combinations of  $\Delta q + \Delta \bar{q}$ , as Eq. (4) shows. There is no direct way of separating  $q$  and  $\bar{q}$  contributions, there is no direct access to polarized sea distributions. This, instead, is possible in semi-inclusive DIS,  $\ell N \rightarrow \ell h X$ .

The double spin asymmetry for the  $\gamma^* N \rightarrow h X$  process,

$$A_1^h \equiv \frac{d\sigma^{\vec{\Rightarrow}} - d\sigma^{\vec{\Leftarrow}}}{d\sigma^{\vec{\Rightarrow}} + d\sigma^{\vec{\Leftarrow}}}, \quad (9)$$

where the arrows now refer to the  $\gamma^*$  ( $\rightarrow$ ) and nucleon ( $\Rightarrow, \Leftarrow$ ) spin configurations, is given by

$$A_1^h(x, Q^2) = \frac{\sum_q e_q^2 [\Delta q D_q^h + \Delta \bar{q} D_{\bar{q}}^h]}{\sum_q e_q^2 [q D_q^h + \bar{q} D_{\bar{q}}^h]} [1 + R]. \quad (10)$$

$A_1^h$  is related by a simple kinematical factor to the measured asymmetry  $A_{\parallel}^h$ ,  $R(x, Q^2)$  has the usual expression in terms of the unpolarized structure functions<sup>4</sup> and the  $D_q^h(z, Q^2)$ 's are the fragmentation functions, which now act as different weights for the  $\Delta q$  and  $\Delta \bar{q}$  terms.

Eq. (10) can be rewritten in terms of purities<sup>10</sup>, computable from unpolarized distribution and fragmentation functions, which relate measured quantities to polarized quark distributions. First data on  $\Delta q_V \equiv \Delta q - \Delta \bar{q}$  and  $\Delta \bar{q}$  are available from HERMES<sup>11</sup> and much more are expected.

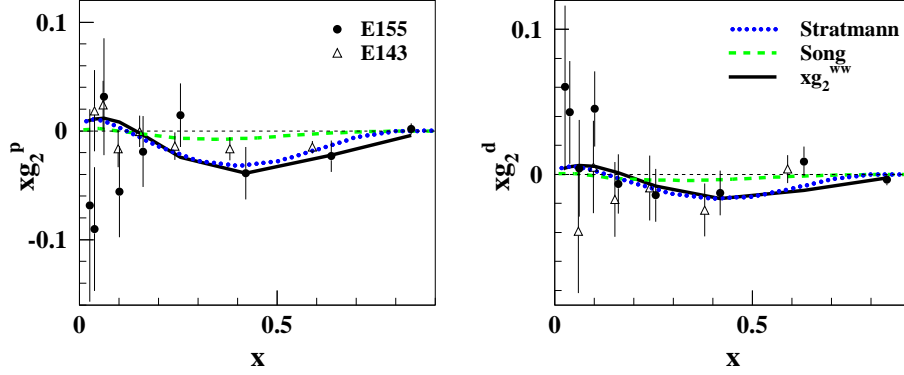


Figure 2: E155 data on  $g_2$ , and comparison with twist-2 Wandzura-Wilczek contribution (solid line); see Ref. [5] for more details.

#### 4 The polarized structure function $g_2(x, Q^2)$

New data on the polarized structure function  $g_2$  have been recently published<sup>5</sup>, see Fig. 2, still with large errors and in limited  $x$  and  $Q^2$  ranges.  $g_2$  has higher-twist contributions, and no direct partonic interpretation; it can be written as the sum of a twist-2 contribution (the so called Wandzura-Wilczek piece<sup>12</sup>) and a higher-twist part:

$$g_2(x, Q^2) = -g_1(x, Q^2) + \int_x^1 \frac{dy}{y} g_1(y, Q^2) + g_2^{\text{H-T}}. \quad (11)$$

A recent paper<sup>13</sup> has studied the scale dependence of flavour singlet contributions to  $g_2$  and given an approximate expression of the higher-twist part in terms of quark and gluon correlations. This expression satisfies the Burkhardt-Cottingham sum rule<sup>14</sup>  $\int_0^1 g_2 dx = 0$ .

Data do not allow yet to extract the higher-twist contribution.

#### 5 Orbital angular momentum

As partons in a nucleon are not collinear, according to angular momentum conservation in the emission of a gluon by a massless quark, the total helicity of a nucleon satisfies the spin sum rule

$$\frac{1}{2} = \frac{1}{2} \Delta \Sigma(1, Q^2) + \Delta g(1, Q^2) + L_q(Q^2) + L_g(Q^2) \quad (12)$$

where  $\Delta\Sigma(1, Q^2) = \sum_q [\Delta q(1, Q^2) + \Delta\bar{q}(1, Q^2)]$  is twice the total helicity carried by quarks,  $\Delta g(1, Q^2)$  is the total helicity of gluons and  $L_{q,g}(Q^2)$  is the total component of the orbital angular momentum of quarks, gluons along the motion direction.

The issue of  $L_q$  and  $L_g$  is a subtle and controversial one; one should wonder whether or not each of the terms in the above equation is gauge invariant, interaction independent, measurable and related to an integral over a parton  $x$  distribution. I urge the reader to consult the recent clear discussions on this subject by Jaffe<sup>15</sup>.

The outcome is that some proposed angular momentum operators<sup>16</sup> for the different contributions to the nucleon spin, whose matrix elements in a nucleon state might be measurable in deeply virtual Compton scattering, do not have a parton interpretation and are not gauge or interaction independent; on the other hand, for some other definition of angular momentum operators<sup>15</sup> which do not suffer the same problems, there is no known way of measuring the corresponding matrix elements.

From the analysis of Ref.<sup>8</sup> the orbital angular momentum contribution at the initial scale is  $L_{q+g}(\mu^2) \simeq 0.15$ .

## 6 Skewed parton distribution

Having mentioned the deeply virtual Compton scattering, I have at least to comment on a very important issue, actually a whole new investigation region, which has also important spin aspects<sup>17</sup>: that of the skewed or off-forward or generalized parton distributions. These are defined as the matrix elements between different nucleon states of the same operators which, in the diagonal case, define the unpolarized and polarized partonic distributions. In different limits, infact, the skewed parton distributions, give the partonic distributions or the elastic nucleon form factors.

Such distributions represent a novel field of investigation, offer new and deeper insights into the nucleon structure and detailed measurement programs at JLAB, HERMES or at new dedicated machines have been discussed; these off-forward matrix elements between polarized nucleon states generalize helicity and transversity distributions.

## 7 Transversity

The trasverse polarization of quarks inside a trasversely polarized nucleon, denoted by  $h_1$ ,  $\delta q$  or  $\Delta_{Tq}$ , is a fundamental twist-2 quantity, as important as the unpolarized distributions  $q$  and the helicity distributions  $\Delta q$ . It is given

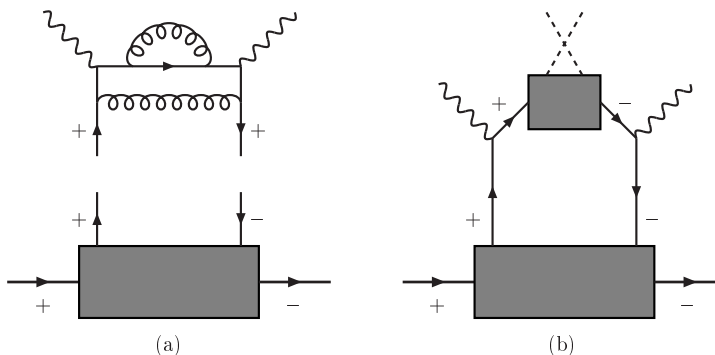


Figure 3: The chiral-odd function  $h_1$  (lower box) cannot couple to inclusive DIS dynamics, even with QCD corrections; it couples to semi-inclusive DIS, where chiral-odd non perturbative fragmentation functions may appear.

by

$$h_1(x, Q^2) = q_{\uparrow}^{\uparrow}(x, Q^2) - q_{\downarrow}^{\uparrow}(x, Q^2) , \quad (13)$$

that is the difference between the number density of quarks with transverse spin parallel and antiparallel to the nucleon spin. It is the same as the helicity distribution only in a non relativistic approximation, but it is expected to differ from it for a relativistic nucleon.

When represented in the helicity basis [see Fig. 3]  $h_1$  relates quarks with different helicities, revealing its chiral-odd nature. This is the reason why this important quantity has never been measured in DIS: the electromagnetic or QCD interactions are helicity conserving, there is no perturbative way of flipping helicities and  $h_1$  decouples from inclusive DIS dynamics, as shown in Fig. 3a.

However, it can be accessed in semi-inclusive DIS, where some non perturbative chiral-odd effects may take place in the non perturbative fragmentation process, Fig. 3b. Indeed, a serious program to measure  $h_1$  in semi-inclusive DIS at HERMES, where a transversely polarized proton target will soon be available, is in progress. We outline here two possible ways of measurement<sup>18</sup>.

### 7.1 $h_1$ and the Collins function

The fragmentation process of a transversely polarized quark into a hadron (say a pion) can have, according to Collins suggestion<sup>19</sup>, a spin and intrinsic  $\mathbf{k}_{\perp}$



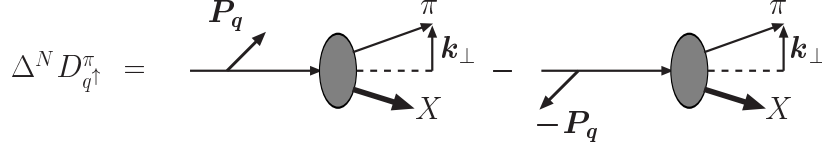


Figure 4: Pictorial representation of Collins function; notice that a similar function is sometimes denoted by  $H_1^\perp$  in the literature.

dependence:

$$D_q^h(\mathbf{p}_q, \mathbf{P}_q; z, \mathbf{k}_\perp) = \hat{D}_q^h(z, \mathbf{k}_\perp) + \frac{1}{2} \Delta^N D_{q^\uparrow}^h(z, \mathbf{k}_\perp) P_q \sin \Phi_C. \quad (14)$$

The quark with momentum  $\mathbf{p}_q$  decays into a hadron with momentum  $\mathbf{p}_h = z\mathbf{p}_q + \mathbf{k}_\perp$  ( $\mathbf{k}_\perp \cdot \mathbf{p}_q = 0$ ).  $\mathbf{P}_q$  is the transverse quark polarization and the Collins angle  $\Phi$  is the azimuthal angle between  $\mathbf{P}_q$  and  $\mathbf{k}_\perp$ . The Collins mechanism is depicted in Fig. 4.

As a consequence, a single transverse spin asymmetry in the process  $\ell p^\uparrow \rightarrow \ell \pi X$  can arise, at leading twist, from the coupling of the chiral-odd transversity distribution  $h_1$  with the chiral-odd Collins function  $\Delta^N D_{q^\uparrow}^\pi$ :

$$A_N^h = \frac{\sum_q e_q^2 h_{1q}(x) \Delta^N D_{q^\uparrow}^h(z, \mathbf{k}_\perp)}{2 \sum_q e_q^2 q(x) \hat{D}_q^h(z, \mathbf{k}_\perp)} \frac{2(1-y)}{1+(1-y)^2} P \sin \Phi_C, \quad (15)$$

where  $P$  is the magnitude of the transverse (with respect to the  $\gamma^*$  direction) nucleon polarization.

Such an asymmetry has been observed for pions by HERMES<sup>20</sup> and SMC<sup>21</sup> revealing that both  $h_1$  and the Collins functions must be large<sup>22</sup>; it promises to be – apart from the importance of showing the Collins effect – a viable access to the first measurement of  $h_1$ .

## 7.2 $h_1$ and $\Lambda$ polarization

Another way of accessing  $h_1$  in semi-inclusive DIS is by measuring the transverse  $\Lambda$  polarization in the process  $\ell p^\uparrow \rightarrow \ell \Lambda^\uparrow X$ . At leading twist this is given by

$$P_\perp = \frac{\sum_q e_q^2 h_{1q}(x) \Delta_T D_q^\Lambda(z)}{\sum_q e_q^2 q(x) D_q^\Lambda(z)} \frac{2(1-y)}{1+(1-y)^2} \quad (16)$$

and it couples  $h_1$  to the chiral-odd transversity fragmentation  $\Delta_T D_q^\Lambda = D_{q^\uparrow}^{\Lambda^\uparrow} - D_{q^\downarrow}^{\Lambda^\downarrow}$ .  $\Lambda$  polarization is easily detectable via its angular decay distribution.

## 8 $\Lambda$ polarization in semi-inclusive DIS

A measurement of  $\Lambda$  polarization in polarized or unpolarized semi-inclusive DIS – both with neutral and charged current contributions – is very interesting in general and it allows to obtain new information on polarized distribution and fragmentation functions and to test at a subtle level the elementary dynamics. The following cases have been considered, with all possible spin configurations<sup>23</sup>:

$$\begin{aligned} \ell N &\rightarrow \ell \Lambda X & \nu N &\rightarrow \nu \Lambda X \\ \nu N &\rightarrow \ell \Lambda X & \ell N &\rightarrow \nu \Lambda X . \end{aligned}$$

## 9 Bloom-Gilman duality and elastic proton form factors

I conclude by mentioning two recent interesting results from JLAB. The first comes from the rich transition region from small to large  $Q^2$  and it is a confirmation of the validity of the Bloom-Gilman duality – the “average” value of the structure functions in the bumpy resonance region agrees with the large  $Q^2$  behaviour – for the polarized structure function  $g_1$ <sup>24</sup>.

The second concerns a measurement – which unfortunately might be the last one for a long time – of the proton elastic form factors, defined in the  $\gamma^* p$  elastic coupling by

$$\Gamma_{\text{em}}^\alpha = F_1(Q^2) \gamma^\alpha + \frac{\kappa}{2M} F_2(Q^2) i \sigma^{\alpha\beta} q_\beta \quad (17)$$

where  $\kappa$  is the proton anomalous magnetic moment. An old perturbative QCD prediction favoured the large  $Q^2$  behaviours

$$F_1 \sim \frac{1}{Q^4} \quad F_2 \sim \frac{1}{Q^6} \quad (18)$$

whereas the surprising result found at JLAB by the Hall A collaboration<sup>25</sup> shows that for  $Q^2$  between 2 and 4 (GeV/c)<sup>2</sup>

$$Q F_2(Q^2) \sim F_1(Q^2) . \quad (19)$$

Preliminary results seem to confirm such a behaviour up to  $Q^2 = 6$  (GeV/c)<sup>2</sup>.

This result has immediately prompted some interesting theoretical considerations related to the role of quark transverse motion and orbital angular momentum<sup>26</sup>.

## 10 Conclusions

I simply conclude by reminding some of the most recently obtained results and of the next ones expected, both theoretically and experimentally, in DIS spin physics.

- Estimate of  $\Delta g(x, Q^2)$  from QCD evolution in inclusive DIS and from direct measurements in other processes;
- measurement of  $g_2(x, Q^2)$  and evaluation of its higher-twist component;
- theory of  $h_1(x, Q^2)$  and its measurement;
- theory of quark and gluon orbital angular momentum and intrinsic  $\mathbf{k}_\perp$ ;
- theory and measurement of off-forward parton distributions;
- single azimuthal asymmetries in semi-inclusive DIS, new data with transversely polarized targets;
- $\Lambda$  polarization in polarized and unpolarized semi-inclusive DIS, with neutral and charged currents; first measurement of polarized fragmentation functions;
- flavour decomposition of spin distributions;
- $\Delta q$  at very large and small  $x$ ;
- elastic electromagnetic proton form factors;
- higher-twists, exclusive reactions, transition from low to large  $Q^2$ , ...

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